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Regional Timber Yield and Cost Information for the South: Modeling Techniques

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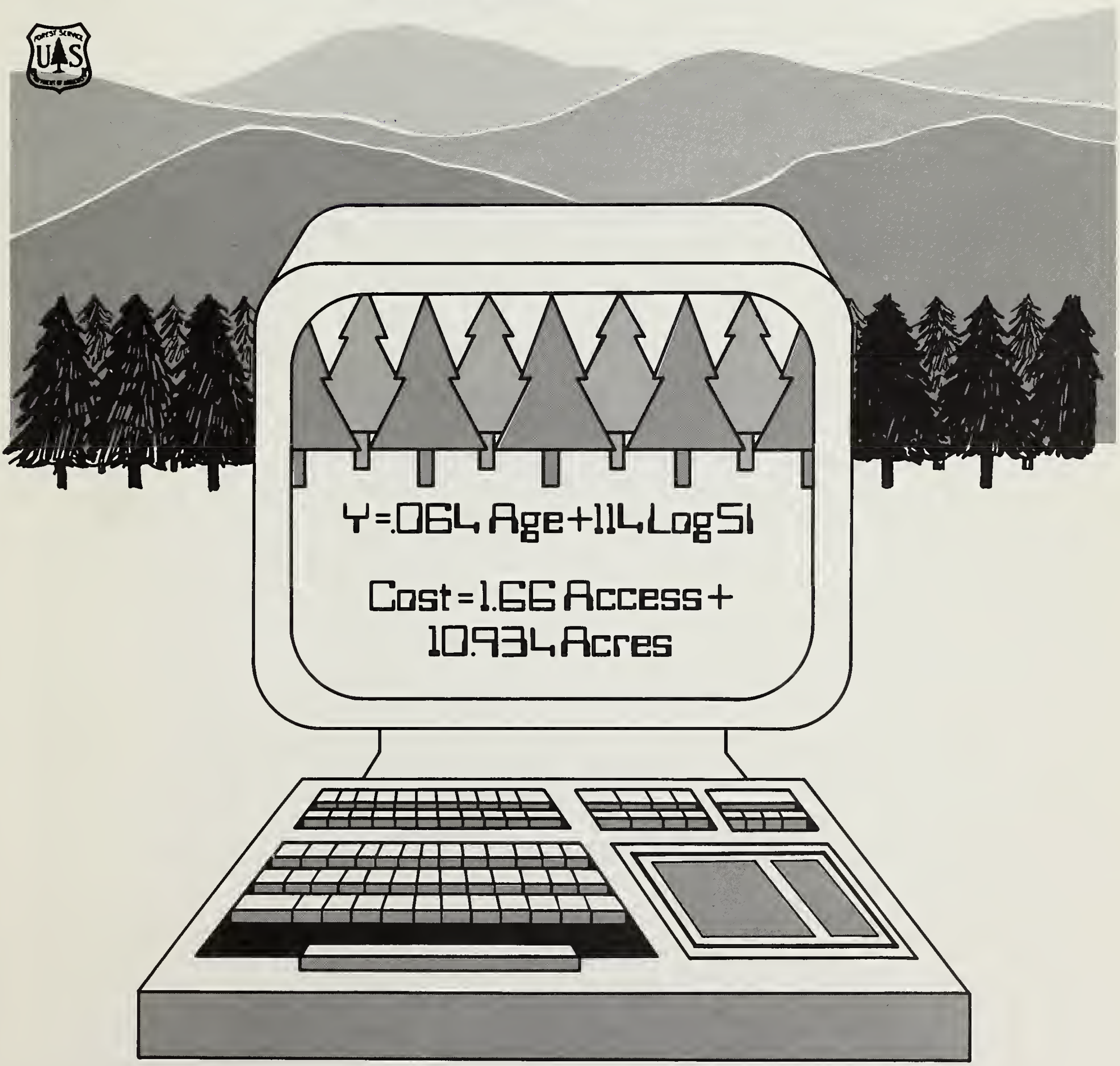

Abstract

This report surveys analytical techniques for estimating the timber production of southern forests under various forestland management alternatives, and associated costs of those management alternatives. The integration of information from growth and yield modeling with timber management cost information in regional timber studies also is examined. Appendixes summarize the nature of data used to develop the timber growth and yield models, inputs required and outputs provided by the timber growth and yield models, and availability of cost information for different forestland management practices.

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INTRODUCTION

Both the public and private forest sectors utilize analyses of regional timber supply trends in formulating forest management policies. In past analyses, most of the projected increase in U.S. timber product output in the next several decades is based on southern timber resources (USDA Forest Service 1982). The potential responses of timber stands to a wide variety of different land management regimes are essential information elements in these regional timber supply analyses.

This report surveys (1) methods for predicting southern timber production under different management alternatives, and (2) the economic costs of management alternatives. These analysis techniques have been developed primarily for use at the stand level. Estimates of regional timber productivity involves balancing loss of relevant detailed information in aggregation with "costs of detail." Both biological and economic information is needed to estimate the economic costs of producing different amounts of timber. These cost functions can help explain how the amount of timber supplied by timber owners is influenced by different levels of economic incentives (e.g., stumpage prices, government subsidies).

The report is intended primarily as a reference document for regional timber supply analysts. It provides a review of major analytical techniques useful in long-range studies of southern timber supplies and expands on a brief presentation of timber inventory projection models by Alig et al. (1984).[4] This report summarizes information useful in analyzing the timber growth and yield and associated management costs in the South. Several related surveys have been published (Burkhart 1975, 1981; Farrar 1979b); however, these do not include management costs. Annotated bibliographies of general growth and yield information (i.e., not limited to yield projection methods) are also available for the major southern pines (Williston 1975) and southern hardwoods (Miller 1967, 1974), but they also do not address the complete set of biological and economic data required in timber supply analysis.

[4]A related survey of timber growth and yield models is given in the following report: Parks, Peter J. 1982. Survey of analytical techniques for estimating southern forest production possibilities. Final report for USDA Forest Service Contract PO 43-82LM-2-72, 63 p. Copy on file at the Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Regional timber supply analyses examine a broad range of complex biological and economic interrelationships at coarse aggregate levels. The FRES ecosystem classification (Garrison et al. 1977) has been used to classify approximately 188 million acres of commercial forestland in the South by cover type (table 1). Approximately 50% is in the southern pine and oak-pine types, and the majority of the remainder (31%) is in the oak-hickory type. Forest management activities, including site preparation, regeneration, intermediate stand treatment, and harvest activities, were performed on 3.3 million acres in 1978 (NFPA 1980). In addition, more than 100 million acres of private, commercial forestland in the South were estimated capable of returning a real rate of return of 4% or more if certain management practices are applied (USDA Forest Service 1981b).

Management practices considered here were identified in the 1980 Resources Planning Act (RPA) Assessment (USDA Forest Service 1981b). Panels of forestry experts in each state identified opportunities for economic investments in forest management (in addition to those expected to be completed under the perceived current level of management). Five groups of investment opportunities were identified according to the type of timber treatment that was needed (table 2). The classes of management considered for the midsouth region (Alabama, Arkansas, Louisiana, Mississippi, Oklahoma, Tennessee, and Texas) were softwood opportunities: density control, regeneration of nonstocked acres, and

Table 1.—Area of southern commercial forestland classified by FRES ecosystem[1]

FRES no.	FRES ecosystem	Area	
		thousand acres	*percent*
10	White-red-jack pine	370.3	0.2
11	Spruce-fir	7.9	0.0
12	Longleaf-slash pine	16,754.7	8.9
13	Loblolly-shortleaf pine	46,576.0	24.8
14	Oak-pine	30,469.7	16.2
15	Oak-hickory	58,939.1	31.3
16	Oak-gum-cypress	26,062.3	13.9
17	Elm-ash-cottonwood	3,243.3	1.7
18	Maple-beech-birch	424.7	0.2
	Nonstocked	5,197.8	2.8
Total		188,045.8	100.0

[1]Based on USDA Forest Service (1982) data.

Table 2.—Definitions of timber treatment classes utilized in regional investment opportunity analysis in 1980 RPA Assessment

Treatment class	Generalized definition
Density control	Represents a broad group of silvicultural options often referred to as "intermediate stand treatments." In general, the class includes precommercial thin, prescribed burn, clean, release, and commercial thin. Certain areas of the country added specific variations. Minor variations were reflected throughout the U.S., but the underlying goal was some managerial treatment that would improve the residual stand of hardwoods or pines to enhance volume and value growth.
Stand conversion	Reflects decisions to harvest or clear existing stands of low-value or low-growth hardwoods and replace them with favored coniferous species. Selection of a method of regeneration depended upon the availability of desirable advance reproduction or a natural seed source, but in most cases resulted in recommendations to clear, site-prepare, and plant.
Regenerate nonstocked land	Nonstocked land is defined as commercial forestland less than 16.7% stocked with growing-stock trees. Recommended treatments of these acres throughout the country was to site prepare and plant the appropriate coniferous species for the geographic region.
Harvest and regenerate hardwoods	Recommendation includes harvest of mature bottomland stands of hardwoods in the Southeast with site preparation for natural regeneration.
Harvest and regenerate softwoods	Harvest and regeneration of mature and overmature softwood stands. Method of regeneration selected depended on availability of seed source and present-net-worth comparison of natural and artificial regeneration. In most cases, artificial regeneration provided higher present net worth.

Source: USDA Forest Service (1981b).

harvest and regeneration of existing stands. The softwood treatment opportunity classes for the Southeast region (Florida, Georgia, North Carolina, South Carolina, and Virginia) were density control, stand conversion, regenerating nonstocked acres, and harvest and regeneration of existing stands. The hardwood treatment opportunity in the Southeast was regeneration to hardwoods.

Nontimber forestland management practices are not directly considered in this report; however, responses of timber stands to nontimberland management practices can be modeled, in some cases, if the management practice can be translated into effects on timber growth and yield parameters (e.g., reduction in basal area). The only forest output considered in this survey is timber. Nontimber forest products and services are produced by forestland management; but, separating the individual costs (per output category) in a variable joint production process is not theoretically tenable (Hof 1983). In addition, supporting data pertaining to technical production relationships among inputs and outputs for nontimber resources are quite limited.

Only the costs of different levels of inputs utilized in land management practices that were reported in the literature are considered here. While this includes a mixture of variable and fixed costs, it is by no means a complete set of management costs. Harvesting costs are not discussed in this report. See Cubbage and Granskog (1982) and McCollum and Hughes (1983) for recent examples of related studies.

BACKGROUND

The economic framework for timber production involves principles that affect, condition, and control (1) the response of forestland to varying combinations of capital and labor inputs; and (2) the economic returns that accrue to timber-producing forestland after payment of wages and interest to labor and capital. Examination of southern timber production potentials in the context of timber production economics requires a broad understanding of the underlying biological and economic fundamentals. Marginal costs of supplying different quantities of stumpage depend largely on the underlying productivity of the land and the timber management practices applied. Forest product values are required for the estimation of economically efficient levels of timber production, but reviewing studies on these topics is outside the scope of this report. For information on regional timber values, see Adams et al. (1979), Adams and Haynes (1980), Neal and Kenna (1981), USDA Forest Service (1981a), and Wallace and Silver (1981).

The production of timber from forests has been modeled as a neoclassical economic production function (e.g., Hyde 1980, Nautiyal and Couto 1982). From this perspective, management intensity and site quality are important determinants of timber production, although the latter factor is not always identifiable as an input in an economic sense. Associated input costs can be separated into two broad categories: (1) payments to factors of production (e.g., management costs); and (2) the opportunity costs of keeping the land in timber production (Hyde 1980). The relationship between input costs and output values determines the economically efficient management regime (Anderson 1972).

Traditional timber growth and yield models have been viewed as production functions whose only discretionary input is time. These are typically adjusted for site productivity via some productivity index. Most existing information pertains to unmanaged even-aged stands of pine, although some yield functions for uneven-aged stands have recently been reported (Farrar et al. 1984). Empirical growth and yield models can be used to develop economic production functions, which can in turn be used to analyze economically efficient timber production.

Nautiyal and Couto (1982) analyze output-input relationships using elasticities. The elasticities of output with respect to various inputs provide a measure of

their individual contributions to the timber production process. Elasticities of scale describe the relative increase in timber output attributable to a proportional increase in all inputs. Output-input relationships, as measured by elasticities of substitution, characterize the curvature of production function isoquants, and indicate the relative ease with which inputs can be substituted for each other. For example, Adams et al. (1982) suggest that the South has significant opportunities for increasing growth through intensive management. One method of quantifying these increases could be to analyze the relevant elasticities.

Both physical growth and yield for different sites, species, and management practices (e.g., yield change after fertilization) and the costs of such practices must be estimated, as demonstrated by Vaux (1954, 1973) in an earlier analysis of timber-growing potential in California. Considerably more published information is available on the growth and yield of timber than for the associated costs of management practices. Nevertheless, costs of production are a crucial consideration when estimating the quantity of timber supplied by timber owners in response to economic incentives. Given the input and output relationships for a particular forest type and site class, assigning costs to the inputs permits estimation of costs for different output levels. For example, Vaux (1973) calculated the aggregate amount of timber that could be grown at or below various maximum average costs per unit of output.

MODELS OF TIMBER GROWTH AND YIELD

Models of southern timber growth and yield have evolved from yield tables for fully stocked, unmanaged, natural stands to computerized models that are applicable to a wider range of stand density regimes and management practices. As models evolved, the methods used to project future timber inventories (growth, mortality, accumulated stock, and structure) in the South (Alig et al. 1984) have changed. When comparing alternative growth and yield models, a useful approach is to first separate the models into two broad classes—direct and indirect methods. Direct methods are applied locally to the same stand from which the data used for projection purposes are obtained. In contrast, indirect methods develop estimates from a sample set of stands and interpolate relationships found for other stand conditions within the bounds of the sample set (Davis 1966). These methods will be reviewed after evaluation criteria have been discussed.

EVALUATION CRITERIA

Specific criteria for evaluating the usefulness of southern timber growth and yield models in regional timber supply analyses are not readily discernable from the literature. Before specific evaluation criteria can be applied, the objectives or goals and the associated information needs of regional timber supply analyses must be defined. Two general evaluation criteria have been applied in this report: (1) extrapolation or flexibility, and (2) validation. These two categories are central to a model's applicability.

Extrapolation considerations include the appropriateness of the growth and yield relationships for use in constructing area-specific variants of the model. The range of data used to construct a model (e.g., ages, density levels) is a particularly important consideration because extrapolation beyond the range may result in inaccurate prediction by the model components (e.g., site index curves, tree volume equations). Appendix 2 provides the reported ranges and limitations of southern growth and yield models.

Validation criteria of growth and yield models are more quantitative than the evaluation criteria. However, the completeness and consistency of validation procedures and results are far from ideal. Validation of long-range timber production models has received limited discussion in the literature. In particular, the importance of accurate representation of real-world timber growth and yield processes or systems has not been adequately discussed. Few articles have described the accuracy of any model in detail. Furthermore, articles about validation of simulation techniques are often philosophical in nature rather than containing practical recommendations or guidelines (Law and Kelton 1982).

Major validation considerations include the following:

1. The data used to validate the model should be independent from data used to develop the model.
2. The model should be validated on the basic outputs it produces. For example, a model that produces diameter-class attributes should be validated on the diameter-class attributes, rather than aggregated stand attributes.
3. Statistical residuals of the validation data set should be similar to those generated by the original data set.
4. Trends in model predictions should follow trends in the validation data set.
5. The model should not exhibit a large amount of bias (i.e., predictions should not be consistently above or below the validation data) (Hann 1980).

In general, test statistics relating to the development of the model (e.g., statistical significance of predictor variables) in most growth and yield studies are not given. Several past studies have required that all variables included in an equation be above a given significance level. Validation results are most commonly presented in terms of mean differences between actual and predicted values. Bias is frequently examined by testing the statistical hypothesis that mean difference is zero. Plot selection criteria usually lead to slight positive bias, with yield predictions representing potential yield rather than actual yield. Most studies provide information on the "fit" of the equations to the data (e.g., multiple correlation coefficient (R^2), standard error of estimate).

These two categories of evaluation criteria provide some broad guidelines for judging model performance. They are not comprehensive criteria that would support

a critical examination. Because each timber supply analysis has its own specific objective, evaluation of specific growth and yield projection methods cannot be rigorously pursued in this review.

DIRECT METHODS

Direct methods of growth and yield projection techniques involve analysis of a particular stand in terms of measured variables (Davis 1966, Avery and Burkhart 1983). The most familiar direct method is stand table projection, in which a sample of growth rates is obtained and applied directly back to the same stand to project growth. Stand tables are composed of frequency data showing number of trees classified by species, diameter at breast height (d.b.h.), or height. Stand tables, commonly expressed on a per-acre basis, depict the stand structure or distribution of tree sizes and species in a stand. Stand table projection models use estimates of future diameter growth, removals, mortality, and ingrowth to adjust the stand table over time.

Direct methods have typically been used to address localized, individual-stand development questions in the South. An exception is application of the stand table projection approach in the Timber Resource Analysis System (TRAS) (Larson and Goforth 1970, Alig et al. 1982), which has been employed in regional and national timber assessments. To answer these broader aggregate stand- or forest-level questions, the assumption is made that a large, regional inventory can be treated as one all-aged stand. The TRAS model is based on an exponential size class distribution, the Q-method, to simulate the growth of large aggregations of individual even-aged and uneven-aged forest stands (Larson and Goforth 1974).

The TRAS model was not designed to accommodate timber management shifts required in recent timber supply studies (Alig et al. 1984), especially changes in management intensity by age classes for the even-aged types in the South (i.e., changes in region-wide age structure). The TRAS model combines treated and untreated forest acreage to attain weighted average acres; this precludes modeling the response to individual timber treatments by specific age classes or other strata (i.e., all acres are treated equally). A package of timber treatments is assumed to be applied across all "average" acres in an ownership aggregate (e.g., softwoods on nonindustrial lands in the Southeast), phasing them in over time by adjusting radial growth increments for each diameter class over a simulation period (Barber 1980). In this aggregate approach, the total growth increment to be phased in is taken from the RPA regional investment opportunity analysis (USDA Forest Service 1981b).

Other models that are designed for a more disaggregated or detailed approach include the Timber Resource Inventory Model (TRIM) (Tedder 1983). Forest acreage in TRIM is stratified by age classes and descriptions for ownership, site, species, and stocking level. Yield tables (e.g., McClure and Knight 1984) constructed for different levels of timber management or investment for these strata are basic inputs into the TRIM systems.

The Southern Pine Age-class Timber Simulator (SPATS) developed by Brooks (1984) for the Southeast and South-central regions is an investment-sensitive age-class model with a level of aggregation that is intermediate between the TRAS and TRIM approaches. SPATS models three different softwood-related types: (1) pine plantations, (2) natural pine, and (3) oak-pine. One average site class is employed for each type. The softwood timber inventories in the South are projected separately for two private owner groups—forest industry and other private—in 5-year intervals. Investment functions in the SPATS model, driven by market forces and government policy actions, select timber management practices to be simulated to allow evaluation of the effect of cost-share payments on future timber supplies and prices.

INDIRECT METHODS

With the advent of large, high-speed computers, several sophisticated methodologies are now used to predict timber production. The most widely used techniques are whole stand models, diameter distribution models, and individual-tree models. Examples of each type of model are listed in appendix 1. Information on data used to develop these models and the resultant outputs are provided in appendixes 2 and 3.

Whole Stand Models

In the whole stand approach, aggregate stand volumes are projected from stand-level variables such as age, site index, or basal area per acre. Usually, no information is provided on volume distribution by size class, but in a few cases merchantable, sawtimber, and pulpwood volumes can be estimated. Since the original work by MacKinney and Chaiken (1939), multiple regression techniques have been used frequently. Most of the available models are of this type, especially for natural stands. The computational simplicity of most whole stand models allows rapid execution on computers.

The introduction of "compatible" growth and yield models was a major development in whole stand modeling. A growth model is compatible with a yield model when yield may be obtained through mathematical integration of growth over time. Clutter (1963) developed compatible models for cubic foot volume growth and yield in loblolly pine. Sullivan and Clutter (1972) later revised Clutter's models in an attempt to overcome two statistical problems: (1) dependent parameters within a system of equations; and (2) nonindependent observations from remeasured plots. They simultaneously estimated current and future stand volume as a function of initial stand age, initial basal area, site index, and future age. Brender and Clutter (1970) first applied this simultaneous estimation technique.

Further refinements in parameter estimation techniques for compatible or simultaneous models include development of such cubic foot volume and basal area projections by Burkhart and Sprinz (1984) and Murphy (1983). Compatible models have also been developed for slash pine (Bennett 1970, Matney and Sullivan 1982), shortleaf pine (Murphy and Beltz 1981, Murphy 1982), longleaf pine (Farrar 1979a), and yellow-poplar (Schlaegel and Kulow 1969, Beck and Della-Bianca 1972). With a few exceptions for thinned plantations (Sullivan and Williston 1977, Lohrey 1979, Matney and Sullivan 1982, Bailey and Ware 1983, and Burkhart and Sprinz 1984), compatible models developed to date are for thinned natural stands. Current stand volume is predicted from age, site, and basal area (i.e., density). Future basal area is predicted from present basal area, present age, and future age, and, sometimes, site index. An equation to predict future volume is obtained by substituting the future basal area equation and future age in the original volume equation.

Whole stand models that provide yield estimates for a variety of units of measure or merchantability standards frequently develop volume ratios to convert a basic yield to various forms. Occasionally (Beck and Della-Bianca 1975, Farrar 1979a, Murphy 1982) these ratios were developed separately to supplement existing models (Beck and Della-Bianca 1972, Farrar 1979a, Murphy and Beltz 1981, respectively). Typically, either volume ratios, basal area ratios, or volume-basal area ratios are dependent variables predicted from stand-level variables relating to the age, basal area, volume, and sometimes, site index of the stand or tree size. With a few exceptions (Bennett et al. 1959; Burkhart et al. 1972a, 1972b; Goebel and Warner 1969), whole stand models also provide future basal area estimates.

Diameter Distribution Models

Similar to the whole stand approach, the diameter distribution approach uses information typically collected in a conventional inventory (age, site, and density). However, this approach can deliver information for any stand table fraction, up to the whole stand. Diameter distribution models are useful for multiple-product analyses because they provide information by diameter classes. For example, Bennett and Clutter (1968) developed multiple-product (sawtimber, pulpwood, and gum) yield tables for slash pine plantations. Almost all diameter distribution models currently available are for pine plantations (appendix 1); exceptions are the Beck and Della-Bianca (1970) and Schreuder et al. (1979) models for natural stands of yellow-poplar and slash pine, respectively.

For the diameter distribution technique, parameters of a probability density function (PDF) are estimated from stand characteristics. The relative frequency distribution of diameters within the stand is used with total frequency to construct a stand table (i.e., tree frequency table by diameter class). The typical sequence of events is: (1) average tree heights are predicted for each diameter class; (2) average volume per tree is calculated using a tree-volume equation or integrated stem profile function; (3) volume per class is calculated using volume per tree and trees per class. Aggregate volume for any fraction of the stand can be calculated by summing the appropriate diameter classes. Projections through time can be made by estimating future diameter class density (i.e., trees per acre) and repeating the process. Compatible growth and yield models have also been developed using the diameter distribution method (e.g., Strub et al. 1981).

The key difference between diameter distribution models is in the PDF used to describe the diameter distribution. Initial applications of this technique used the beta PDF (Bennett and Clutter 1968, Lenhart and Clutter 1971, Lenhart 1972, Burkhart and Strub 1974). Most recent applications have used either the Weibull PDF (Clutter and Belcher 1978, Dell et al. 1979, Feduccia et al. 1979, Lohrey and Bailey 1977, Matney and Sullivan 1982, Smalley and Bailey 1974a, 1974b), or the Johnson S_B (Hafley and Schreuder 1977), S_{BB} (Schreuder and Hafley 1977), or S_{BBB} (Schreuder et al. 1982a, 1982b) PDF's.

Computational procedures for diameter distribution models are relatively efficient. In a study by Daniels et al. (1979b), execution time on a computer for the Burkhart and Strub (1974) diameter distribution model was 0.25 seconds per stand estimate. Execution times for the whole stand model (Burkhart et al. 1972b) and the individual tree model (Daniels and Burkhart 1975) were 0.01 and 13.78 seconds, respectively.

Versatile tree volume-defining equations, or integrated stem profile functions, used in the diameter distribution approach provide an opportunity to diversify the outputs from these models. Yields per tree can be obtained in any units (e.g., board feet, cords, dry weight, etc.) inherent in tree-volume functions. It is often possible to use several different tree-volume equations or a stem profile function to obtain volume estimates in a variety of units of measure. Most diameter distribution models are capable of producing basal area estimates for any fraction of the stand because tree frequency by diameter class is known or estimated.

Burkhart (1971) evaluated the accuracy and precision of the diameter distribution yield estimation for old-field slash plantations developed by Bennett and Clutter (1968) through an independent sample in south Georgia and north Florida. He concluded that, for large samples, yields of old-field slash pine plantations can be reliably predicted by the Bennett-Clutter technique. Variation of individual plots may be relatively large, but on the average the technique gives accurate results.

Individual-Tree Models

A common characteristic of the variable density growth and yield models discussed above is their reliance upon aggregate stand or size class characteristics such as basal area or number of trees for modeling of forest development. The most recent approach for modeling forest growth and yield is use of individual-tree simulation models. Stands are described

on the basis of characteristics of individual trees, which are then combined to form stands. These models consider a set or list of individual trees and associated tree or stand characteristics for a plot. They simulate the growth of each tree by explicit or implicit "potential" growth functions; these, in turn, are modified by expressions reflecting competition due to number and size of associates (Ek 1977). In this manner, tree spatial locations and individual tree characteristics influencing tree growth and yields may be explicitly considered. There are two general classes of individual-tree models: (1) those that do not require intertree distances, and (2) those that require intertree distances as a necessary input (Munro 1974).

Distance-Independent Models

Individual-tree distance-independent models classify the competitive status of the subject tree by comparing its characteristics (size, crown ratio, etc.) in relation to all other trees in a sample plot. Each sample tree is weighted with an expansion factor—the number of trees per acre it represents.

The advantages of this type of model are that it can be used for any age structure or species mixture and it provides relatively detailed information on tree and stand parameters and on the effects of stand management. Disadvantages include its relative complexity and the inability to predict the growth of specific single trees with high reliability (Munro 1974). All of the individual-tree models described herein are similar because they involve some type of tree accounting, product conversion, and summary capability. Actual stand dynamics are also simulated by specific program sections or subprograms for survivor tree growth, mortality, and, sometimes, ingrowth or regeneration. There may also be subprograms for management activities, such as harvesting or thinning. Specific options for insect and disease impact studies and habitat analyses have also been developed.

Individual-tree distance-independent models have been employed to simulate growth and yield for individual forest stands, small forested areas, and for entire states in other parts of the country (Alig et al. 1984). Aggregation capabilities of these models, potential costs of adapting them to large-scale assessments, the number of plots needed to represent forest conditions in regional timber assessments, and model validation require further examination (Alig et al. 1984). An individual-tree model capable of projections for 20 species may be no more complex (and probably less so) to construct and use than 20 "simpler" models for 20 different species.

No individual-tree distance-independent models for southern forest types have been reported in the literature. One proposal is the calibration of the Stand and Tree Evaluation and Modeling System (STEMS), formerly known as the Forest Resources Evaluation Program (FREP) (USDA Forest Service 1979, Moeur and Ek 1981) for use in the South. STEMS is an individual-tree distance-independent model designed to describe stand development, with or without management activities. STEMS can be used to update or project stand development or to evaluate various silvicultural management alternatives. The model has several timber management options available. The model's timber growth projection system has been applied in the Lake States (Jakes and Smith 1980) and can model a variety of forest conditions, including pure or mixed stands. Southern biological response equations need to be developed and tested for even-aged and uneven-aged stand conditions to allow the STEMS system to be used for the South.

Distance-Dependent Models

The second type of individual-tree model requires intertree distances as an input. In these models, "individual trees" on a plot are assigned certain initial size and spatial distributions. The trees are "grown" according to some function of their size, site, and competitive status. Sometimes a random adjustment is made for microsite and/or genetic variability (e.g., Daniels and Burkhart 1975). Competitive status for each tree is quantified in terms of a competition index that is a function of the tree's size and the distance to and size of its neighbors. Mortality is usually a function of competition index, tree size, and/or growth. Yield estimates are made by applying volume equations to the estimated dimensions of the trees (Curtis 1972), as in other individual-tree models and diameter distribution models.

Advantages of individual-tree distance-dependent models over distance- independent forms are that (1) growth estimates are possible for specific individual trees and (2) explicit treatment of location may make it easier to assess the effects of area-specific agents (e.g., diseases). Possible disadvantages of this type of model are that they require (1) intertree distances as an input (not usually inventoried), (2) a meaningful competition index for individual trees, (3) more computing time; also, (4) predictions are often stochastic, and (5) the plots that are simulated are small and perhaps uncharacteristic of the stand.

An example of a single-tree distance-dependent model is the PTAEDA model developed by Daniels and Burkhart (1975). The PTAEDA model simulates the growth of loblolly pine under a wide range of management alternatives. The two major subsystems in PTAEDA deal with the generation of an initial precompetitive stand and the growth and dynamics of that stand. After PTAEDA was developed for old-field stands, subroutines were added to simulate the effects of site preparation, fertilization, and thinning on tree and stand development (Daniels and Burkhart 1975). Trees are "grown" annually according to their size, site quality, and intertree competition. The probability of survival for each tree is calculated from a function relating each tree's individual vigor and its competitive stress as measured by estimates of photosynthetic potential. Growth is adjusted stochastically to simulate genetic and microsite variability. Survival probability is used to stochastically determine annual mortality.

Effects of certain management practices are incorporated into PTAEDA by modifying the original growth function through subroutines to simulate the effects of site preparation, thinning, and fertilization on tree and stand development (Daniels and Burkhart 1975). The efficiency of site-preparation is expressed as the degree to which a cutover site approaches old-field conditions. Growth reductions on cutover land are assumed to be due solely to competing vegetation, because degradation in site quality caused by past management practices could be described by initially specifying a lower site index (Daniels and Burkhart 1975). Similarly, the response to fertilizer treatments could be described as an increase in site quality, as suggested by Ek and Monserud (1974) and Hegyi (1974). For this reason, a site adjustment factor that acts as a multiplier for site index for fertilized stands is built into the model.

An individual-tree model has also been developed for seeded loblolly pine (Daniels et al. 1979a). However, the growth and mortality components had been developed for plantations. Initial results indicate a need to calibrate these relationships for seeded stands (Daniels et al. 1979a). In regard to computing time requirements for single-tree distance-dependent models, Daniels et al. (1979b) found execution time per stand estimate for the PTAEDA model was 55 times that of the diameter distribution model constructed by Burkhart and Strub (1974) and 1,378 times that of the whole stand model developed by Burkhart et al. (1972b).

GROWTH AND YIELD INFORMATION BY FRES ECOSYSTEM AND TIMBER TREATMENT CLASSES

The majority of the different classes of models discussed above provide growth and yield information that applies to even-aged forest types. More specifically, most of the models are for plantations and natural stands in the loblolly-shortleaf and longleaf-slash pine FRES ecosystems.

Other models pertain to thinned upland oak-hickory (Dale 1972), unthinned bottomland hardwoods (Smith et al. 1975, Gardner et al. 1982), and thinned and unthinned yellow-poplar (Schlaegel and Kulow 1969, Beck and Della-Bianca 1970, 1972, 1975). The models by Smith et al. and Gardner et al. can be used for the oak-gum-cypress FRES ecosystem, while Dale's work can be applied to the oak-hickory FRES ecosystem. Because yellow-poplar is commonly present in the oak-hickory type, the models for this species may also be useful in modeling this ecosystem's timber production.

Hepp (1981) incorporated most available growth and yield information by forest type into eleven simulator subroutines in a FORTRAN computer program called YIELD. The user enters stand conditions and financial data and can obtain stand-level growth, yield, and financial analyses. The eleven simulators model seven even-aged forest types: loblolly pine, longleaf pine, shortleaf pine, slash pine, eastern white pine, yellow-poplar, and upland oak. Yield estimates for thinned and unthinned stands of the southern pines, yellow-poplar, and upland oak are possible. A modification of the program was designed to meet information needs for implementation of linear programming models in National Forest System (NFS) Region 8.

A program similar in concept to YIELD has been developed for loblolly pine by Myers (1977a). The program, YLDTBL, uses available loblolly pine growth and yield information to predict value and yield of planted stands, over the site range of the species, under various management alternatives. Timing and severity of thinnings, length of rotation, and type of harvest can be modified to compare the effects of various management strategies on timber yield. The program can be modified for use with other species, provided that the necessary growth and yield informaton is available (Myers 1977a). A modified version of YLDTBL that provides yield estimates of both loblolly pine and deer forage has also been published (Myers 1977b). Input variables include stand prescriptions, controls on management, stumpage prices, and costs of various activities and practices. The program is applicable to loblolly pine plantations in east Texas and Louisiana, but (subject to the same information needs as YLDTBL) can be readily modified for other species or areas (Myers 1977b).

GENERAL COMPARISONS OF TIMBER PRODUCTION MODELS

Timber inventory projection models applied in the South have been developed following direct and indirect strategies. Direct methods, such as TRAS, have been used in most large-scale timber supply analyses. Generalized stand table projection models use conventional timber inventory data and are relatively simple and inexpensive to use, but they need a large data base, cannot easily model different forest management schemes, are conceptually difficult to interpret, and reliable tree size and distribution information for smaller areas is hard to extract. Recent research to improve southern pine growth and yield modeling for large geographical areas includes techniques based on age-class representation of the timber inventory.

Indirect methods have been more widely applied. Whole stand models predict stand-level volumes from stand-level characteristics and comprise most of the timber production models located in the literature. Compatible whole stand models allow future timber volume to be derived via mathematical integration of timber growth with respect to time. Age, site, and density are used in predicting stand volumes in whole stand models. Diameter distribution models use Beta, Weibull, and Johnson S_{BBB} probability density functions to represent the distribution of the tree diameters within age site, and density classes. These models can provide volume information by size or diameter classes or aggregations of diameter classes. Individual-tree models simulate stand development using the individual tree as the basic growth unit. The only species in the South that has been

modeled on an individual-tree basis is loblolly pine (Daniels and Burkhart 1975).

Timber production models for other than pure pine types are not numerous. Management regimes that contain one or several thinnings can be simulated at the stand level for specific stand conditions, but the simulation of timber management at more aggregate levels is not well developed. Quantitative guidelines are also not well developed for estimating the progression of understocked and overstocked stands.

Although uneven-aged management of southern pine under the selection system may be an attractive management alternative for many nonindustrial forestland owners, few timber production models are available for uneven-aged stands (Murphy and Farrar 1982, 1983; Farrar et al. 1984). Most uneven-aged modeling has been for mixed hardwood species. The predictor variables most frequently used in models for uneven-aged stands are density (basal area or numbers of trees) and elapsed time. A generally accepted site quality measure has not been established for uneven-aged stands but even-aged site index (estimated from suitable trees) or soil-site index have interim utility.

COST INFORMATION

Information on the cost of providing timber under various forestland management alternatives is required for an economic analysis of timber production. As Samuelson (1976) states, costs and productivity returns are merely opposite sides of the same relationship. The total cost of producing any level of timber output consists of both variable and fixed components. The magnitude of the fixed cost component does not vary with the level of output. A cost function consists of an explicit function of the level of timber management inputs multiplied by the variable cost per unit of input, plus the cost of the fixed inputs.

Forest management costs involve complex, interdependent interactions among the factors of production—capital, labor, land, and other materials. The variety of input combinations used to produce timber is controlled by their marginal rate of technical substitution and relative costs of the inputs. Factors of production can be substituted for each other over a finite output range, although the relatively long period of production allows for many possible adjustments for intertemporally linked investments on a particular ownership.

Three basic alternative methods for estimating the total costs of producing different levels of outputs in economic analyses are: (1) classification of costs for a process into fixed, variable, and semivariable components using an accounting framework, on the basis of inspection and judgment; (2) estimation of the relationships of cost to output on the basis of engineering conjectures and past cost behavior; and (3) determination of the functional relationship of cost to rate of output by statistical analysis of recorded cost, output, and other operating conditions (Dean 1966). These approaches need not be mutually exclusive. Often two or more of them are used together, as shown in the following summary of reported cost information across RPA timber treatment classes (A = accounting/survey, S = statistical or econometric estimates, D = Delphi estimates):

Management practice	Type of information
A. Regeneration	
1. Site preparation	
a. Mechanical for planting	A, S
b. Seedbed preparation	A, S
2. Artificial	
a. Machine planting	A, S
b. Hand planting	A, S
c. Seeding	S
3. Stand or type conversion	A, D
B. Density control	
1. Chemical removal	A, S
2. Prescribed burning	A, S
3. Release cutting	A
4. Thinning	
a. Precommercial	A
b. Commercial (harvesting costs)	A
C. Other	
1. Fire protection	D
2. Insect and disease protection	—

ACCOUNTING/SURVEY APPROACH

The accounting/survey approach involves classification of timber management costs based on inspection and surveys. One problem is that fixed, variable, and semivariable costs have usually not been separated out for the timber management practices; other problems also exist. Economies of scale have not been accounted for in most forestry cost surveys (e.g., unit cost declines with more acres treated), although unit costs by different acreage or volume classes could be estimated (Row 1978, Cubbage 1983). Categories of management practices used over the years have also varied, as has the embodied technology, which hampers trend analysis. Fluctuations in such factors as wage rates and material prices can usually be corrected for by utilizing a price or cost index to convert estimates to constant dollars.

Cost averages for forestry practices have been calculated from a series of surveys of individuals, public agencies, and private firms in the South over the period 1952–1979 (Moak 1982). These surveys were initiated by Worrell (1953); they are listed in appendix 4. The surveys provide average cost estimates for the following treatments: prescribed burning; mechanical site preparation; planting by hand and machine; chemical removal of undesirable trees; timber cruising; harvest marking; mechanical seedbed preparation in established stands; and cutting to release young growth. The southern states are stratified into three regions: the Southern Coastal Plain, which includes the area south of

the Savannah River and below the fall line in Georgia westward along the Gulf Coast; the Northern Coastal Plain, which includes the area north of the Savannah River and east of the fall line; and the Piedmont, which includes the region in the Southeast between the fall line and the mountains plus the upland areas from Alabama westward through Arkansas.

The costs are further classified according to site characteristics (more difficult than average, average, less difficult than average) and cost components (direct labor, supervision, equipment, overhead). Moak (1982) analyzed the trends in costs of forest practices in the South and compared them with various price trends, and concluded that costs have increased relatively sharply over the past three decades.

Sunda and Lowry (1975) also used a survey technique to develop cost estimates for three different types of loblolly pine regeneration practices: seed-tree, shelterwood, and planting. Twenty land management companies, agencies, or consultants were asked to supply cost information on loblolly pine regeneration procedures performed in 1973 and 1974. The area examined in this study is east Texas, Louisiana, and Arkansas. Cost estimates were similar to those reported for the Southern Coastal Plain by Moak and Kucera (1975).

For each of the three methods, three cases were considered: exceptionally favorable conditions; average conditions; more difficult conditions—especially with regard to hardwood competition. All cases were analyzed for an even-aged stand of loblolly pine harvested at age 40. The elements of regeneration cost considered were: mechanical site preparation (four possible methods); chemical hardwood control; precommercial thinning; marking trees for seed sources; prescribed burning; and planting by hand or machine. The regeneration method and case being analyzed determine which particular cost elements contribute to the total cost of each regeneration scenario (Sunda and Lowry 1975).

The accounting approach provides no way to correct timber cost data explicitly for changes in technology or other conditions that influence cost behavior. These conditions must remain constant for accurate results to be obtained.

ENGINEERING/DELPHI APPROACH

Experience with technical requirements of timber production, including observation of past input requirements and cost behavior, can be used to make systematic conjectures about cost behavior for prospective management practices. The engineering method relies upon expert knowledge and pooled judgments of practical operators (Dean 1966). It also has been characterized as the "synthetic" method—building up descriptions of cost functions from detailed study of components in a production process and integrating those components to represent the total production process.

The Delphi approach has probably been more widely used in natural resource management, where a team of experts evaluates historical cost behavior to improve their judgments. Two typical features of the Delphi technique are:

1. There is more than one round of questioning—that is, the experts are asked for their opinions on each question more than one time.
2. Controlled feedback is provided. Respondents are told about the group's responses on the preceding round. On later rounds, respondents with extreme answers are asked to provide reasons, and these reasons are summarized anonymously for the next round.

The engineering and Delphi methods are similar. Both rely on experience and judgment, although to varying degrees. Engineering cost estimates are typically constructed in physical units. The man-hours required are converted into dollars at current or prospective prices. The engineering method may be replaced by the Delphi method when experience and records do not provide an adequate historical basis for measuring cost behavior. Engineering and Delphi estimates also supplement statistical or accounting analyses when it is necessary to project cost behavior beyond the range of past timber management experience, or to estimate the effects of major technological or scale changes upon cost behavior.

Information requirements of regional or national timber supply assessments often require that regional forestry experts be convened and asked to provide estimates of costs and other information elements that are not available from other sources. In some cases this is to fill information gaps; in others it may extend to almost complete development of needed data bases. Two examples of this procedure in forestry are the regional timber investment panels utilized in the USDA Forest Service (1981a, 1981b) study, and the multiresource production experts for the Ashton et al. (1980) study.

There is a vast literature on the Delphi technique, but comparatively little empirical work is available on the advantages of several key aspects of the Delphi techniques (e.g., iterative procedure and feedback) over the typical mail survey. Armstrong (1978) is critical of the attention that the Delphi technique has received in forecasting. Sackman (1974) states that the accuracy of this technique is necessarily suspect so long as Delphi questions are not empirically linked to objective and independently verifiable criteria. Sackman concludes that the technique is essentially unreliable and scientifically unvalidated. However, these liabilities are counterbalanced somewhat by the immediate need to apply this technique in some natural resource supply analyses where the notion of expert opinion, low cost, convenience, and simplicity of the method make it attractive.

STATISTICAL APPROACH

The statistical approach uses multiple regression or other statistical techniques to estimate a functional relationship between cost and timber output. Hence, the statistical method can accommodate more variation in underlying conditions than the accounting approach

because variations can be accounted for by using explanatory variables.

Statistical analysis of timber production cost behavior can use either cross-sectional data (simultaneous observation of costs of different, but similar, timber treatment areas) or time series data (sequential observation of costs for identical treatment opportunities over a period of time). Cross-sectional observations are more common in forestry than time series data, which require many years to accumulate. The difference between cross-section and time series data is somewhat analogous to temporary plots versus remeasurements.

A difficulty with using cross-sectional data is that it is not easy to locate enough treatment areas for an adequate sample. The areas need to be sufficiently similar in resource condition, management methods, and records. They must also differ in size to analyze economies of scale. For the use of time series data, it is not likely that technology, management methods, and other conditions have remained essentially constant over the time required to collect a sufficient number of time series data points. In some cases, cross-sectional and time series data can be pooled to help circumvent such problems (Judge et al. 1982).

Econometric techniques, which use economic theory, mathematical economics, and statistical inference as an analytical foundation for quantifying relationships among economic variables, have been used to estimate costs of timber production. Statistical or econometric estimation is generally based on nonexperimental cost data, where observations of a system are not subject to experimental control. This contrasts with the data in growth and yield studies based on experimental designs. Further, cost studies have usually been conducted independently of the growth and yield studies discussed earlier. Consequently, geographical bases, definitions, etc., may differ markedly between these sets of studies, making comparison and cross-reference difficult.

Nationwide studies by Row (1971) and Mills et al. (1984), based on Forest Service contract data, present cost averages and predictive equations. Row used contracts from FY 1970, stratified according to management practice, method of application, and forest type. Mills et al. used contracts from FY 1975 through FY 1978, stratified according to management practice and forest type. Forest types used to classify the contracts in both studies are Forest Survey types, which are essentially equivalent to the FRES types discussed earlier. Both Row and Mills et al. found it necessary to aggregate several FRES types to obtain sufficient sample sizes. Row found it necessary to aggregate all eastern FRES types to obtain sufficient sample size to develop a regression relationship, including contracts in the Northeast and the Southeast.

Row used 850 of the 1019 contracts awarded in FY 1970. Only combinations of management practice, method, and forest type represented by more than 10 contracts were analyzed. Some of the management practices (e.g., site preparation) could be performed by any of several methods. The equations developed are for: (1) complete site preparation using a bulldozer with blade; and (2) site preparation using a bulldozer with rake. The equations predict total cost (including Forest Service equipment, labor, materials, and direct administrative cost) and are based on 12 and 15 observations, respectively.

The econometric model developed by Row predicts total cost for each contract as the sum of a fixed cost per contract and a variable cost per acre times the number of acres in the contract. The variable cost per acre is a function of a basic variable cost for each practice-method-forest type combination, acres per tract in the contract, relative accessibility of the tract, and difficulty of the terrain (in terms of obstacles). Each observation was weighted according to its size in acres because the variability in cost was higher for smaller contracts. Weighting in this manner compensates for heteroscedasticity among the observations, permitting a valid regression relation to be developed (Row 1971).

Mills et al. (1984) stratified Forest Service contracts from FY 1975 through FY 1978 according to forest type and management practice. The four practices analyzed are: (1) site preparation for seeding, planting, or natural regeneration, consisting of burning, low intensity preparation, or high intensity preparation; (2) reforestation by hand or machine planting or seeding; (3) intermediate treatment, including precommercial thinning, timber stand improvement, individual or area tree release by aircraft, hand, or machine; and (4) slash disposal.

Aggregate forest types used by Mills et al. (1984) are southern pine and central hardwoods. Equations developed for these aggregate forest types predict direct cost (defined as contract cost plus the cost of Forest Service materials used in the contract) for the following forestry practices: site preparation for southern pine; reforestation for southern pine; intermediate treatment for southern pine; and site preparation for central hardwoods. These equations were based on 126, 74, 28, and 68 cases, respectively.

Equations developed by Mills et al. (1984) are based only on variables currently known or easily estimated. To select the variables used, a statistical screening procedure is used to determine which variables are most significant. From these, an all-possible value covariance matrix is calculated, and variables with simple correlations of 0.80 or greater are identified. One of the two correlated variables is excluded from further analysis in that stratum. From the covariance matrix, a set of all possible regression equations is developed. The regression in this set that has the least unexplained variability (as measured by Mallow's C_p statistic) is withdrawn for further analysis.

Variables present in this regression are noted, and observations complete in these variables are used to calculate a second all-possible value covariance matrix. From this second matrix, a second set of all-possible regression equations is calculated. The regression equation in this second set of equations that has the least unexplained variability is used as the final equation (Mills et al. 1984).

Vasievich (1980) also used Forest Service information to develop an econometric relationship to predict the cost of hazard reduction burning. He analyzed 408 hazard reduction burn plans from Coastal Plain national

forests extending from South Carolina to Texas. The burns were all successfully completed from 1972 to 1975. Equations were developed to predict man-days of labor, chains of plow line, and chains of fireline. The dependent variables are the size of the burn area (acres) and the age of the rough (i.e., years since last burn). Overhead, direct, and indirect costs were derived from these equations using assumptions and supplemental information provided in the paper.

Overhead costs cover fixed expenses that are necessary for a burning program but that cannot be related to a specific burn. These costs are assumed to be a fixed percentage of all direct and indirect costs. Indirect costs are for such items as planning and transportation of labor and equipment. Direct costs are outlays for labor, materials, and equipment to plow firelines before the burn, to do the burning itself, and to mop up afterward. Costs are expressed in 1976 dollars and compare closely with the Moak et al. (1977) cost estimates. The Vasievich (1980) costs are slightly lower, possibly because average burn size is larger or because only successfully completed burns are considered (Vasievich 1980).

INTEGRATION OF TIMBER PRODUCTION AND COST INFORMATION

Cost studies of timberland management practices have usually been conducted independently of growth and yield studies. However, several studies have combined cost information with growth and yield information, usually for the financial analysis of timber management decisions at the stand level in the South. Review of these studies can help identify the "weak links" for these integrated analyses, in the context of the (relative) value of possibly obtaining additional information for different study components.

One of the more comprehensive models that integrates a broad range of timber growth/yield and cost information for southern ecosystems is the Georgia Supply (GASPLY) model (Montgomery et al. 1976, Robinson et al. 1978). GASPLY, which is based on a FORTRAN computer program, estimates the long-run timber supply from even-aged forests in Georgia. The GASPLY model aggregates USDA Forest Service survey plots into acreage cells, each homogeneous with respect to region, subregion, forest type, owner, site quality, and physiographic class. Three management plans are analyzed—custodial, natural stand, and plantation. The custodial plan implies no management and minimal costs; property taxes are the only cost outlay. The specific elements of the cost of the natural stand and plantation plans reflect currently accepted methods of regeneration and management. Costs and benefits included in each plan are compared on a perpetual rotation basis; maximum present net worth is the criterion used to assign a plan to a cell.

The user of GASPLY specifies a long-run demand equation, and GASPLY will develop a management prescription that will meet long-run quantity demanded. Because maximum present net worth is the criterion used to select optimal management plans, the GASPLY prescription is economically efficient (Robinson et al. 1978). Robinson et al. (1981) used GASPLY to develop an economic growth goal for the Southeast. The area covered in this study (Florida, Georgia, North Carolina, South Carolina, and Virginia) is stratified into three physiographic areas: the Coastal Plain, the Piedmont, and the mountains. Five forest types were defined: longleaf-slash pine, loblolly-shortleaf pine, oak-pine, upland hardwoods, and bottomland hardwoods. Yield equations for natural stands and plantations of loblolly and slash pines were adapted from Coile and Schumacher (1964) and Schumacher and Coile (1960). Yields for hardwood stands were developed from Knight's (1978) analysis of USDA Forest Service survey plots in North Carolina and Virginia. Stumpage prices were developed from Timber Mart-South price reports (Norris 1976); cost estimates were obtained from a survey of industrial timberland managers, National Forest managers, and State Foresters' staffs (Robinson et al. 1981).

In another regional study, the USDA Forest Service (1981a, 1981b) describes economic opportunities to increase softwood production on private lands. This study used the TRAS model discussed earlier and the Timber Assessment Market Model (TAMM) (Adams and Haynes 1980) to project long-run timber supply, and summarized the results of TAMM projections for four levels of investment. These investment levels are comprised of different intensities and schedules of the timber treatment classes described in Table 2. Two of the investment levels give special attention to private lands; they include immediate investments in softwood management on private lands beyond those expected to occur under continuaton of present management. The array of investments are presented that would return 4% and 10% real rates of return.

Costs given are the total present value of the cost (per cubic foot and per acre) for the investment (Table 2) plus the discounted value of any follow-up costs associated with each treatment. Treatment costs given for the Southeast region are: (1) control, including precommercial thinning, prescribed burning, stand cleaning, release from competition, and commercial thinning; (2) stand conversion, which reflects a decision to harvest or clear low-value or low-growth hardwoods and replace them with pine; (3) regenerating nonstocked land (defined as less than 16.7% stocked with growing stock trees) including site preparation and planting; (4) regenerating hardwoods, consisting of harvesting bottomland hardwoods and preparing the site for natural regeneration; and (5) harvest and regeneration of the existing stand. Costs presented for the Midsouth region are: (1) stocking control; (2) regenerating nonstocked acres; and (3) harvest and regeneration of the existing stand (USDA Forest Service 1981b).

Timber investment analyses at the stand level include that by Anderson and Guttenberg (1971) for the conversion of mixed oak-pine stands to stands of pure pine. They constructed investment guides by using growth and yield information reported by Bennett and Clutter (1968) and Lenhart (1968) for slash and loblolly pine. An average conversion cost of $40 per acre was used.

Anderson (1972) used these yield models to derive economically oriented production functions. The functions are developed from size-class data. Per-acre volumes and cumulative number of trees in percent are given for 20-, 25-, and 30-year production periods on medium and good sites. Such yield information is useful in determining economically efficent rotation length.

Weaver and Osterhaus (1976) derived investment schedules for planted loblolly pine from regeneration costs and regeneration scenarios developed by Sunda and Lowry (1975). Loblolly pine yields and prices were adapted from Anderson and Guttenberg (1971) and Dierauf and Marler (1965). Using this information, Weaver and Osterhaus calculated the net present value of the regeneration cases discussed by Sunda and Lowry for low, medium, and high quality site classes.

Hardie (1977) used dynamic programming to determine an optimal thinning strategy and rotation length for planted loblolly pine in the mid-Atlantic region. Yield estimates are from a model developed at Virginia Polytechnic Institute and State University. Several economic parameters are varied in Hardie's model. Among these are stumpage price trends, discount factors, costs of plantation establishment, property taxes and other annual charges, sporadic or periodic costs incurred during the rotation, land rent, and trends in costs. Maximum present net worth is the criterion used to select the optimal management plan.

The degree of uncertainty inherent in estimating future components of timber supply in the studies above is strongly related to the aggregation schemes employed, which by their nature condense diverse and complex relationships into a relatively small number of essential characteristics. The broad geographical range of most aggregate analyses that integrate timber production and cost information invariably includes diverse timber resource conditions and potentials. Further, aggregation and uncertainty in timber supply modeling are related in part to the quantity and quality of historical data available as a basis for projection. Although the levels of timber growth and yield data have been augmented substantially during the last several decades, substantial data deficiencies remain for both biological and economic dimensions of timber supply modeling.

OVERVIEW AND CONCLUSIONS

Information for estimating the input and output relationships for southern timber production is largely based on experiments that selected very homogeneous timber stand situations. In contrast, timber yield information for more typical or "woods-run" heterogeneous stands is relatively limited. Although the growth and yield studies have advanced well beyond examination of fully stocked stands, a parallel positive bias presently exists because of selection of uniform plots in managed yield studies. Southern growth and yield information accumulation has accelerated, but some important relationships among timber production inputs and outputs still require further study. For example, long-term studies are necessary to determine the treatment response of stands in terms of diameter distributions and volume of sawtimber, veneer, and poles. Timber production models are only available for a few specified timber management practices for the wide array of stand ages, site qualities, and density levels. The available information is primarily for even-aged pine management, and in particular planted loblolly and slash pine. There are fewer managed yield tables than those for unthinned stands. Geographical applicability of models is sometimes not well specified, and validation techniques have not been widely discussed in the literature.

There is more timber growth and yield information available for even-aged stands than for uneven-aged ones. Research for uneven-aged timber management yields has expanded in recent years (Farrar et al. 1984). Interest in uneven-aged timber management as a practical alternative is increasing, particularly for private nonindustrial ownerships in the South (Murphy 1980). These ownerships comprise approximately three-quarters of the timberland in the region.

Although efforts continue to improve information on the development of stands under specified timber management regimes, additional timber production and cost information is also needed for passive or "no management." Because many stands are not managed actively, the natural transitions among forest types and composition of stands after harvest is an important consideration in long-term timber supply modeling.[5] Studies by Boyce and Knight (1979, 1980) indicate many nonindustrial, private forest owners passively permit the (biologically) better adapted hardwoods to increase naturally after the harvest of pines. Improved fire protection and shifting agriculture have also contributed to changes in the region's distribution of forest types.

Productivity resulting from inputs into timber production can be analyzed using production functions that depict the transformation of inputs into timber output. Technology in timber production consists of a collection of techniques (both available and implemented ones), with each technique represented by a production function. A change in the collection of techniques constitutes technological change, such as implementation of regeneration methods involving genetically improved stock. More intensive timber production methods have been applied in the South, but empirical analysis of related aggregate trends has been limited.

The stochastic nature of timber growth and yield estimates, related to the substantial uncertainty associated with long-term timber production processes, has not been widely discussed in the literature. Deterministic models of growth and yield are often reported without reflecting stochastic tendencies of long-range growth and yield estimates. Impacts on growth and yield from climatic vagaries, fire, insect, or disease epidemics are difficult to predict and depend in part on management and utilization trends. Southern pine beetle effects in the South are being analyzed in a large research ef-

[5] *Alig, Ralph J., James G. Wyant, and Herbert A. Knight. 1983. Analysis of forest type transition in the Southeast. 33 p. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.*

fort, and Reed et al. (1980) have made long-term projections of beetle damage using the TRAS model. Past regional studies, such as USDA Forest Service timber assessments, usually project mortality based on historical patterns.

Much less data has been collected and research conducted on the costs for various forestland management alternatives than for timber growth and yield production. The main source of time series data on costs of forestry practices is a series of related accounting surveys over the period 1952–1979 (Moak 1982). Statistical analyses of timber production cost relationships, based on regression or econometric equations, are the other major source of timber management cost information. These studies are usually based on cost information from Forest Service contracts. Replication or expansion of these types of analyses has been quite limited. Delphi techniques have been used to provide cost estimates in cases where it is not possible to obtain needed information from statistical analyses or surveys.

Past integration of timber production and cost information has been primarily for stand-level analyses. One of the few regional models for the South that combines aspects of timber production and management costs is the GASPLY model. This model can accommodate empirical growth and yield data collected in the major statewide forest resource inventory efforts.

Aggregation of growth and yield and cost information in the analysis of regional timber supply warrants more scrutiny in future studies. Trade-offs need to be examined between two kinds of costs: (1) those derived using variables that are numerous and/or difficult to obtain or estimate, and (2) the costs associated with the unsatisfactory predictions that may result if the number of variables is small, thus sacrificing detailed information.

Aggregation procedures are judged satisfactory by Green (1964) when the cost of more detailed information outweighs the greater reliability of the results that could be obtained by using more detailed information. That judgment depends in part on the purpose of the investigator in conducting regional timber supply studies. Gaging the associated "reliability" of results in long-range timber supply analyses is not likely to be straightforward and may be somewhat subjective in nature.

Green's evaluation of aggregation procedures is related to the concept of "consistent" aggregation, where the use of information more detailed than that contained in the aggregate would make no difference in the results of the analysis. In addition to these theoretical aggregation problems, the integration of timber growth and yield and economic information in timber supply studies is influenced by institutional considerations (e.g., political or administrative groupings) and further complicated by differences in emphasis among disciplines.

In summary, major information needs related to analyses of timber supply in the South include modeling of growth and yield for uneven-aged forest management and the mixed oak-pine FRES types, and costs for implementing most forestland management alternatives. Much more attention has been devoted to the biological and mensurational dimensions of southern timber supply in past data collection and research efforts than to the cost aspects. Differences in underlying study conditions, definitions, and other characteristics create some problems in combining the cost information that has been accumulated with that from growth and yield studies. Significant strides have taken place over the last several decades in addressing such problems, and further improvements in timber supply analysis will depend in part on measures taken to strengthen existing data sources.

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APPENDIX 1

SUMMARY OF TIMBER GROWTH AND YIELD MODELS SURVEYED[1]

Table A1.—Summary of models surveyed

Author	Year	Principal species
WHOLE STAND MODELS		
Plantations		
Bennett et al.	1959	Slash pine
Burkhart et al.	1972b	Loblolly pine
Burkhart and Sprinz	1984	Loblolly pine
Coile and Schumacher	1964	Loblolly, slash pines
Goebel and Warner	1969	Loblolly pine
Lohrey	1979	Longleaf pine
Sullivan and Williston	1977	Loblolly pine
Natural Stands		
Beck and Della-Bianca	1972, 1975	Yellow-poplar
Bennett	1970, 1980	Slash pine
Brender and Clutter	1970	Loblolly pine
Burkhart et al.	1972a	Loblolly pine
Dale	1972	Upland oak-hickory
Farrar et al.	1984	Loblolly, shortleaf pines
Gardner et al.	1982	Hardwoods
Murphy	1982	Shortleaf pine
Murphy	1983	Loblolly pine
Murphy and Beltz	1981	Shortleaf pine
Murphy and Farrar	1982, 1983	Loblolly, shortleaf pines
Murphy and Sternitzke	1979	Loblolly pine
Schlaegel and Kulow	1969	Yellow-poplar
Schlaegel et al.	1969	Yellow-poplar
Schumacher and Coile	1960	Southern pines
Smith et al.	1975	Hardwoods
Sullivan and Clutter	1972	Loblolly pine
DIAMETER DISTRIBUTION MODELS		
Plantations		
Burkhart and Strub	1974	Loblolly pine
Cao et al.	1982	Loblolly pine
Clutter and Belcher	1978	Slash pine
Clutter and Jones	1980	Slash pine
Dell et al.	1979	Slash pine
Feduccia et al.	1979	Loblolly pine
Lenhart	1972	Loblolly pine
Lenhart and Clutter	1971	Loblolly pine
Lohrey and Bailey	1977	Longleaf pine
Matney and Sullivan	1982	Loblolly pine
Smalley and Bailey	1974a	Loblolly pine
Smalley and Bailey	1974b	Shortleaf pine
Smith	1978	Loblolly pine
Natural Stands		
Beck and Della-Bianca	1970	Yellow-poplar
Schreuder et al.	1979	Slash pine
INDIVIDUAL-TREE MODEL		
Plantations		
Daniels and Burkhart	1975	Loblolly pine

[1]*Based on tables provided by Dr. Harold Burkhart, Department of Forestry, Virginia Polytechnic Institute and State University, Blacksburg, Virginia.*

APPENDIX 2

SELECTED CHARACTERISTICS AND NATURE OF DATA USED IN TIMBER GROWTH AND YIELD MODELS

These tables are based on tables 1 and 2 of a report by Burkhart et al. (1981); several additions incorporate information on more recent studies.

Table A2.—Old-field and other plantation models

Model	Geographic location	Stand treatments	Number of observations	Plot size	Range of data: Age	Range of data: Site index 25	Range of data: Density
				acres	*years*	*feet*	*trees/acre*
	OLD-FIELD PLANTATION MODELS						
Loblolly pine							
Burkhart and Strub (1974)	Piedmont and Coastal Plain in Virginia; Coastal Plain in Delaware, Maryland, and North Carolina	Unthinned	186	0.1	10-35	47-84	300-2900
Burkhart et al. (1972b)	Piedmont and Coastal Plain in Virginia; Coastal Plain in Delaware, Maryland, and North Carolina	Unthinned	189	0.1	9-35	47-84	300-2900
Burkhart and Sprinz (1984)	Piedmont and Coastal Plain in Virginia	Thinned	103	0.3	10-40	50-70	--
Cao et al. (1982)	Piedmont and Coastal Plain in Virginia	Thinned	128	0.2	12-30	50-70	355-1305
Goebel and Warner (1969)	Piedmont in South Carolina	Unthinned	200	64	10-25	40-75	500-1400
Lenhart (1972)	Interior West Gulf	Unthinned	219	65	10-30	40-70	500-1200
Lenhart and Clutter (1971)	Georgia Piedmont	Unthinned	226	64	9-33	40-80	750-1650
Matney and Sullivan (1982)	South	Thinned	--	--	--	--	--
Smalley and Bailey (1974a)	Highland in Tennessee, Alabama, and Georgia	Unthinned	267	0.05	10-31	31-89	202-2240
Slash pine							
Bennett and Clutter (1968)	Coastal Plains in Georgia and north Florida	Unthinned	478	--	15-30	50-80	--
Bennett et al. (1959)	Georgia middle Coastal Plain, Carolina sandhills	Unthinned	308	Varied	10-28	30-80	110-5400
Clutter and Jones (1980)	Georgia, Florida, Alabama, and Mississippi	Thinned	212	0.25	9-32	47-80	(Basal area 25-150 ft²/acre)
Shortleaf pine							
Smalley and Bailey (1974b)	Highlands in Tennessee, Georgia, and Alabama	Unthinned	104	Varied, usually 0.05	11-35	26-58	400-4500
	NON-OLD-FIELD PLANTATION MODELS						
Loblolly pine							
Feduccia et al. (1979)	East Texas, Louisiana, southern Arkansas, and southern Mississippi	Unthinned	409	Varied but >0.1	3-45	22-78	250-1500
Smith (1978)	Lower Coastal Plains in Carolinas, Georgia, and north Florida	Unthinned	226	Varied	10-30	20-70	300-900
Sullivan and Williston (1977)	Loessial soils in Arkansas, Mississippi, and Tennessee	Thinned	499	Varied	6-30	60-110	(Basal area 1-139 ft²/acre)

NON-OLD-FIELD PLANTATION MODELS—(Continued)

Table A2.—Old-field and other plantation models—(Continued)

Model	Geographic location	Stand treatments	Number of observations	Plot size	Range of data: Age	Range of data: Site index 25	Range of data: Density
				acres	*years*	*feet*	*trees/acre*
Slash pine							
Clutter and Belcher (1978)	Coastal Plain in Georgia and Florida	Unthinned	487	Varied	--	--	--
Dell et al. (1979)	West Gulf: east Texas, Louisiana, and Mississippi	Same as Feduccia et al. (1979)	399	--	3-32	23-87	250-2500
Longleaf pine							
Lohrey (1979)	South Lousiana, and east Texas	Thinned Unthinned	457	Varied	16-42	33-68	(basal area 40-190 ft^2/acre)
Lohrey and Bailey (1977)	Central Louisiana, and east Texas	Unthinned	260	Varied, 0.10-1.25	16-38	29-73	250-2500
BOTH OLD-FIELD (*) AND NON-OLD-FIELD (**) PLANTATION MODELS							
Loblolly pine							
Coile and Schumacher (1964)	South	Half of the plots were thinned one or more times	370* 28**	0.10 (6-10 yr) 0.20 (>10 yr)	5-35	35-80	--
Daniels and Burkhart (1975)	Piedmont and Coastal Plain in Virginia; Coastal Plain in Delaware, Maryland, and North Carolina	Unthinned	189* 51**		8-35	47-84	300-2900
Slash pine							
Coile and Schumacher (1964)	South	Half of the plots were thinned one or more times	370* 28**	0.10 (6-10 yr) 0.20 (>10 yr)	5-35	35-80	--

Table A3.—Natural stand models

Model	Geographic location	Stand treatments	Number of observations	Plot size	Range of data: Age	Range of data: Site index 25	Range of data: Basal area
				acres	*years*	*feet*	*ft²/acre*
Loblolly pine							
Brender and Clutter (1970)	Hitichi Experimental Forest in Georgia Piedmont	Light thinning or improvement cut	179	Varied	15-70	50-100	10-120
Burkhart et al. (1972a)	Coastal Plains in North Carolina and Virginia; Piedmont Virginia	Unthinned	121	0.10	13-77	53-92	35-217
Clutter (1963)	Georgia, Virginia, and South Carolina	Thinned	[1]102	0.25	21-69	53-110	30-154
Murphy (1983)	South Arkansas, Lousiana, and East Texas	Thinned unthinned	[1]296	Variable radius	> 20-51 +	> 70-101 +	> 20-121 +
Murphy and Sternitzke (1979)	West Gulf: east Texas, Louisiana, and Arkansas	Thinned	145	--	12-85	68-127	17-137
Schumacher and Coile (1960)	Coastal Plain from Chesapeake Bay to Mobile Bay	Unthinned	420	0.20	20-80	60-120	96-198
Sullivan and Clutter (1972)	Georgia, Virginia, and South Carolina	All plots were thinned	102	0.25	21-69	53-110	30-154
Uneven-aged loblolly-shortleaf pine							
Farrar et al. (1984), Murphy and Farrar (1982, 1983)	South Arkansas, and north Louisana	Thinned	[1]310	2.5-40 +	[2]1-18	80-90	> 20-100 +
Murphy and Farrar (1982, 1983)	South Arkansas	Thinned	[1]310	2.5-4.0 +	[2]1-18	80-90	> 20-100 +
Slash pine							
Bennett (1970)	Tampa, throughout east and west Florida to Cordele and Savanna, Georgia	Thinned	82	0.25	20-60	60-100	50-175
Bennett (1980)	South Georgia, north and west Florida	Unthinned Thinned	176 121	0.25 0.25	20-50	60-100	25-175
Schreuder et al. (1979)	Georgia and Florida	Unthinned	175	0.25	17-68	43-104	[3]22-450
Schumacher and Coile (1960)	Throughout commercial slash pine range	Unthinned	231	0.20	20-30	50-100	[3]133-1308

Table A3.—Natural stand models—(Continued)

Model	Geographic location	Stand treatments	Number of observations	Plot size	Range of data: Age	Range of data: Site index 25	Range of data: Basal area
				acres	*years*	*feet*	*ft²/acre*
Longleaf pine							
Farrar (1979a)	Northwest Florida, southwest Georgia, south and central Alabama, and south Mississippi	Thinned	[2]139	0.20	15–80	46–90	8–169
Schumacher and Coile (1960)	Atlantic Coastal Plain	Unthinned	368	0.20	20–80	50–100	[3]165–588
Shortleaf pine							
Murphy and Beltz (1981), Murphy (1982)	West Gulf: east Texas, east Arkansas, Louisiana, and Arkansas	Unthinned	153	--	26–91	44–101	4–94
Schumacher and Coile (1960)	North Carolina, Piedmont	Unthinned	74	0.20	20–80	40–100	93–204
Upland oak-hickory							
Dale (1972)	Kentucky, Ohio, Missouri, Iowa	Thinned	154	Varied, Usually >0.56/acre	22–90	55–89	--
Yellow-poplar							
Beck and Della-Bianca (1970, 1972, 1975)	Appalachian Mtns. of North Carolina, Virginia, and Georgia	Unthinned (1970), thinned (1972, 1975)	141	0.25	17–76	75–138	44–208 (Prior to thinning)
Schlaegel and Kulow (1969)	West Virginia	Unthinned thinned	123	0.1–0.25	26–80	57–110	60–180
Schlaegel et al. (1969)	West Virginia	Unthinned thinned	123	0.1–0.25	26–80	57–110	60–180
Hardwoods							
Gardner et al. (1982)	South	Unthinned	641	0.20	--	--	--
Smith et al. (1975)	South	Unthinned	641	0.20	--	--	--

[1]*Number of plots involved.*
[2]*Elapsed time or cutting cycle length, age is not applicable.*
[3]*Trees per acre.*

APPENDIX 3

INPUTS AND OUTPUTS FOR TIMBER GROWTH AND YIELD MODELS

These tables are based on table 3 from Burkhart et al. (1981), with several additions pertaining to more recent studies.

Table A4.—Whole stand models for plantations and natural stands

Model	Inputs	Outputs
	PLANTATIONS	
Bennett et al. (1959)	Age A Initial spacing Percent survival at age A Site index (base age 25)	Ft³ volumes (ob and ib) to 2-, 3-, and 4-inch tops ob
Burkhart et al. (1972b)	Age A Number of surviving trees/acre at age A Site index (base age 25) Site index (base age 25)	Average height of dominants and codominants Ft³ volumes (ob and ib): total, to 3- and 4-inch tops ob Bd.ft. volumes to 6-inch tops ob
Burkhart and Sprinz (1984)	Ages A1 and A2 Site index (base age 25) Initial basal area	Ft³ volumes (ob): total, to 4- and 6-inch tops ib
Coile and Schumacher (1964)	Age A Number of trees/acre planted or surviving Site index (base age 25)	Number of surviving trees/acre Average height of dominants and codominants Basal area and average dbh Total ft³ volumes ib Feasible to compute ft³ volumes ob to 4-inch tops ib
Goebel and Warner (1969)	Age A Number of surviving trees/acre at age A Site index (base age 25)	Average height of dominants and codominants Ft³ volumes ib: total, to 3- and 4-inch tops ob
Lohrey (1979)	Ages A1 and A2 Site Index (base age 25) Initial basal area (B1)	Projected basal area Ft³ volumes (ob): total Bd.ft. volumes to 8-inch tops ob
Sullivan and Williston (1977)	Ages A1 and A2 Site Index (base age 50) Initial basal area (B1)	Projected basal area Ft³ volumes (ib): to 3-inch tops ib
	NATURAL STANDS	
Beck and Della-Bianca (1972, 1975)	Ages Al and A2 Basal area at age A1 Site index (base age 50)	Basal area at age A2 Ft³ volumes, trees 4.5 inches dbh and larger Bd.ft. volumes for trees 11-inches dbh and larger Mean dbh Mean dominant stand height
Beck and Della-Bianca (1975)	(As above) Height of dominant stand	Bd.ft. volumes for trees 11 inches dbh and larger
Bennett (1970, 1980)	Ages A1 and A2 Basal area at age A1 Site index (base age 50)	Ft³ volumes to 4-inch tops ob. at ages A1 and A2 Bd.ft. volumes of trees 9.6 inches dbh and larger to 8-inch tops (ob) ages A1 and A2 Basal area at age A2
Brender and Clutter (1970)	Ages A1 and A2 Basal area at age A1 Site index (base age 50)	Ft³ volumes to 4-inch tops at ages A1 and A2 Bd.ft. volumes to 8-inch tops at ages A1 and A2
Clutter (1963)	Ages A1 and A2 Site index (base age 50)	Basal area at age A2 Bd.ft. volumes (ib): total

Table A4.—Whole stand models for plantations and natural stands—(Continued)

Model	Inputs	Outputs
	NATURAL STANDS—(Continued)	
Dale (1972)	Age A Basal area at age A Site index (base age 50)	Net annual basal area Growth/acre (2.6-inch dbh and larger) Ft^3 volumes (ob) 2.6-inch dbh and larger Ft^3 volumes (ib) trees 4.6 inches dbh and larger to 4.5-inch tops ob Bd.ft. volumes (ib) trees 8.6 inches dbh and larger to 4.5-inch tops ob
Farrar (1979a)	Ages A1 and A2 Basal area at age A1 Site index (base age 50)	Basal area at age A2 At ages A1 and A2: Total ft^3 volumes (ib and ob) Ft^3 volumes (ib and ob) for trees 3.6-inches dbh and larger to 3-inch tops ob Ft^3 volumes (ib and ob) for trees 9.6 inches dbh and larger to 7-inch tops ob Bd.ft. volumes for trees 9.6 inches dbh and larger to 5-inch tops ib Average diameter
Gardner et al. (1982)	Age A Sapling basal area Pole and sawtimber basal area	Volumes and weights of various stand biomass components
Murphy (1982)	(As above)	(As above) Bd.ft. volumes for trees 9-inches dbh and larger for 4 log rules to 7-inch tops ib
Murphy (1983)	(As above)	Ft^3 volumes for trees 9-inches dbh and larger to 7-inch tops (ob) Bd.ft. volumes for trees 9-inches dbh and larger to 7-inch tops ob at ages A1 and A2
Murphy and Beltz (1981)	Ages A1 and A2 Basal area at age A1 Site index (base age 50)	Basal area at age A2 Ft^3 volumes for trees 5-inches dbh and larger to 4-inch tops (ages A1 and A2)
Murphy and Farrar (1982, 1983)	Elapsed time (cutting cycle) Initial merch. and sawt. basal areas	Projected merchantable and sawtimber basal areas Ft^3 volumes (ib): trees >3.5-inch dbh to 3.5-inch tops (ib) and trees >9.5-inches dbh to 7.5-inch tops ib Bd.ft. volumes for trees >9.5-inches dbh to 7.5-inch tops ib
Murphy and Sternitzke (1979)	(As above)	Basal area at age A2 Ft^3 volumes for trees 5-inches dbh and larger to 4-inch tops ob at ages A1 and A2
Schlaegel and Kulow (1969)	Ages A1 and A2 Site index (base age 50)	Basal area at age A2 Ft^3 volumes (ib): total
Schlaegel et al. (1969)	Basal area at age A1 as above	As above and total ft^3 volumes (ob) Bd.ft. volumes
Schumacher and Coile (1960)	Ages A1 and A2 Basal area at age A1 Site index (base age 50)	Basal area at age A2 At age A1 and age A2: Total ft^{3}volumes ib Bd.ft. volumes to 6-inch tops ib. Average heights of dominants and codominants Number of trees/acre
Smith et al. (1975)	Age A State Percent cover by species	Bd.ft. volumes, and ft^3 volumes Total height at age A
Sullivan and Clutter (1972)	Ages A1 and A2 Basal area at age A1 Site index (base age 50)	Basal area at age A2 Total ft^3 volumes ib at ages A1 and A2

Table A5.—Diameter distribution models

Model	Inputs	Outputs
Beck and Della-Bianca (1970)	Age A Site index (base age 50)	For each dbh class: Total ft^3 volumes and to 4-inch tops (ob) Bd.ft. volumes for trees 11-inches dbh and larger to 9-inch tops (ob)
Burkhart and Strub (1974)	Age A Number of surviving trees/acre at age A Average Height of dominants and codominants	Average height Number of surviving trees/acre Feasible to compute ft^3 volumes (ob and ib): total, to 3- and 4-inch tops ob, using volume equations from Burkhart et al. (1972b)
Cao et al. (1982)	Age A Site index Total basal area and number of trees per acre	Average height Total ft^3 volumes (ob and ib)
Clutter and Belcher (1978)	Age A1 Average height of dominants Number of surviving trees/acre at age A2	For each dbh class: trees/acre at age A2 Average height Ft^3 volumes to 4-inch tops (ob)
Clutter and Jones (1980)	Age A Site index (base age 50) For each dbh class: Trees/acre Average height Average dbh	Number of trees at age A2 Basal area at age A2 Ft^3 volumes at age A2 Bd.ft. volumes at age A2
Dell et al. (1979)	Age A Trees/acre, planted or surviving Site index (base age 25)	Average height and crown ratio Number of trees/acre Ft^3 volumes (ob and ib): total, and to 2-, 3-, and 4-inch tops (ob)
Feduccia et al. (1979)	Age A Number of trees/acre planted or surviving Site index (base age 25)	Average height and crown ratio Number of surviving trees/acre Ft^3 volumes (ob and ib): total, to 2-, 3-, and 4-inch tops ob
Lenhart (1972)	Age A Number of surviving trees/acre at age A Site index (base age 25)	Average height Number of surviving trees/acre Ft^3 volumes (ob and ib): total, to 2-, 3-, and 4-inch tops ob
Lohrey and Bailey (1977)	Ages A1 and A2 Number trees/acre at A1 Height of dominant stand	Number of trees/acre at A2 Basal area/acre at A2 Ft^3 volumes (ib and ob): total, trees 3.5 inches dbh and larger to 4-inch tops (ob)
Schreuder et al. (1979)	Age A Trees per hectare Site Index (Base age 50)	Tree dbh, height, and volume distributions (2 parameter Weibull) Trees per acre by dbh class Mean tree height by dbh class Total volumes (ob) per hectare in m^3 and cords by dbh class and stand
Smalley and Bailey (1974a,b)	Age A Number of trees/acre planted or surviving Site index (base age 25)	Average height Number of surviving trees/acre Ft^3 volumes (ob and ib): total, to 2-, 3-, and 4-inch tops ob
Smith (1978)	Soils group Age A Dominant stand height	Trees/acre by dbh class and total tree height by dbh class Ft^3 volumes: total and merchantable to varying tops (ob) by dbh class and stand

Table A6.—Individual-tree model for plantations

Model	Inputs	Outputs

Daniels and Burkhart (1975)	Age A
	Number of trees/acre planted
	Site index (base age 25)
	Management choices:
	  Spacing pattern
	  Site preparation
	  Thinning
	  Fertilization
		Number of trees/acre planted and surviving
		Average height of dominants and codominants
		Mean dbh
		Basal area and total ft^3 volumes ob

APPENDIX 4
COST STUDIES FOR TIMBERLAND TREATMENT

Table A7.—Timberland treatment cost studies by geographic area

Study	Year	Geographic area	Treatment[1]
Anderson and Granskog	1974	South (slash pine plantations in sandy soil on flat terrain)	Density
Cubbage and Granskog	1982	South (southern pine)	Density
Fight and Dutrow	1981	Southeast	Fertilization
Gardner	1981	South	Artificial reg.
Granskog	1978	South (slash pine)	Density
Granskog and Anderson	1980	South (loblolly pine)	Density
Guldin	1982, 1983	South (southern pine)	Artificial reg.
Hassler et al.	1981	South	Density
Kerr	1982	South	Artificial reg.
Lewis and Chappelle	1964	Virginia	Density
Mills et al.	1984	South	Artificial reg. density, other
Moak and Kucera	1975	Southern Coastal Plain, northern Coastal Plain, Piedmont	Artificial reg., density, other
Moak et al.	1977	Southern Coastal Plain, northern Coastal Plain, Piedmont	Artificial reg., density, other
Moak	1979	Southern Coastal Plain, northern Coastal Plain, Piedmont	Artificial reg., density, other
Moak et al.	1980	Southern Coastal Plain, northern Coastal Plain, Piedmont	Artificial reg., density, other
Moak	1982	South	Artificial reg., density, other
Row	1971	South	Artificial reg.
Schick and Maxey	1978	South	Density
Somberg et al.	1963	South	Artificial reg. density, other
Sunda and Lowry	1975	Texas, Louisiana, Arkansas	Artificial reg., density, other
Tufts et al.	1981	South	Equipment cost index
USDA Forest Service	1981a, 1981b	South	Artificial reg., density
Vasievich	1980	Southern Coastal Plain	Prescribed burning
Weaver and Osterhaus	1976	South (loblolly pine)	Artificial reg.
Worrell	1953	Southern Coastal Plain, northern Coastal Plain, Piedmont	Artificial reg., density, other
Yoho and Fish	1961	Southern Coastal Plain, northern Coastal Plain, Piedmont	Artificial reg., density, other
Yoho et al.	1969	Southern Coastal Plain, northern Coastal Plain, Piedmont	Artificial reg., density, other

[1]*See table 2 for description of timber treatment classes. "Other" refers to practices such as fire protection, marking trees for harvest, slash burning, and timber cruising.*

Alig, Ralph J., Peter J. Parks, Robert M. Farrar Jr., and J. Michael Vasievich. 1984. Regional timber yield and cost information for the South: Modeling techniques. USDA Forest Service General Technical Report RM-112, 28 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

This report surveys analytical techniques for estimating the timber production of southern forests under various forestland management alternatives, and associated costs of those management alternatives. The integration of information from growth and yield modeling with timber management cost information in regional timber studies also is examined. Appendixes summarize the nature of data used to develop the timber growth and yield models, inputs required and outputs provided by the timber growth and yield models, and availability of cost information for different forestland management practices.

Keywords: Regional studies, timberland management, timber supply

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Rocky Mountain Forest and Range Experiment Station

Rocky Mountains

Southwest

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